Limits on the Gunn-Peterson Effect at $z = 5$

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ABSTRACT

We report new limits on the Gunn-Peterson effect at a redshift near 5 using spectroscopic observations of the $z = 5$ Sloan Digital Sky Survey quasar, J033829.31+002156.3, made with the LRIS and HIRES spectrographs on the Keck telescopes. Lower resolution spectrophotometrically calibrated observations made with LRIS over the wavelength region $\lambda\lambda 4500 - 9600$ Å were used to obtain a continuum shape and to flux calibrate much higher resolution ($R = 36,000$) observations made with HIRES. The LRIS data show an Oke D_A index of 0.75. Portions of the HIRES spectrum return to near the extrapolated continuum level. Including both statistical and systematic errors we place an upper limit of $\tau = 0.1$ on the regions of minimum opacity. We argue that, even if this opacity arises in underdense regions of the intergalactic gas, we require a high value of the meta-galactic ionizing flux at these redshifts ($J_\nu \gg 4 \times 10^{-23}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at $z \sim 4.72$) to produce a solution which is consistent with even minimum nucleosynthesis estimates of the baryon density. We also report the presence of a Mg II absorption system of extremely high equivalent width ($W_{\lambda,rest}(2796) = 1.73$ Å) at $z = 2.304$.

Subject headings: cosmology: observations — early universe — intergalactic medium — quasars: absorption lines

1. Introduction

Soon after the discovery of cosmologically distant objects it was realised (Field 1959) that the absence of strong Lyman alpha scattering of light at the appropriate redshifted wavelengths placed strong constraints on the amount of neutral hydrogen in the intergalactic medium (Shklovskij 1964; Scheuer 1965; Gunn & Peterson 1965). The absence of significant neutral opacity in a uniformly distributed component of the IGM is generally referred to as the Gunn-Peterson effect.

While it remains conceptually possible that there is a diffuse substrate of the IGM in a multi-phase gas, modern interpretations of the Lyα forest of neutral hydrogen absorption lines suggest instead that the IGM is a highly structured warm ionized gas in which the amplitude of the perturbations grows gravitationally. In this interpretation the Lyα forest is produced by scattering from the very small neutral hydrogen fraction of this undulating density intergalactic gas (e.g., Cen et al. 1994; Zhang, Anninos, & Norman 1995). Regions of minimum H I optical depth, in this scenario, occur in cosmic mini-voids, which are underdense expanding regions where growth is essentially frozen (Meiksin 1994; Reisenegger & Miralda-Escudé 1995). The cosmic mini-voids are the closest analogs in this model to the Gunn-Peterson effect in a homogeneous diffuse gas, and the simple physics of these regions makes them powerful probes of the metagalactic ionizing flux relative to the baryon density of the universe.

Because of the rapid increase in the gas density with redshift, it is expected that the fraction of the quasar spectrum returning to the continuum level will diminish rapidly at the higher redshifts. As a specific example, Zhang et al. (1997) find, at $z = 5$, for $H_0 = 50$ km s^{-1} Mpc^{-1}, $\Omega_b = 0.06$ and a Haardt-Madau (1996) spectrum and ionizing flux, that less than a fraction of a percent of the spectrum will have $\tau(\text{H I}) < 0.1$. Moreover, they find that the spectrum of a $z = 5$ quasar will have an average flux in the region between 1050 Å

and 1170 Å that is 10% of the continuum value which would be present in the absence of Lyman alpha scattering.

The newly discovered $z = 5$ quasar J033829.31 + 002156.3 (Fan et al. 1999) presents an opportunity to look at this question at the highest redshift yet available, and we report here low and high resolution spectral observations of this object. As Schneider, Schmidt, & Gunn (1991b) found in the $z = 4.897$ quasar PC1247+3406, $1 - D_A$ (the Oke index D_A is defined in §3) is higher than the model values (0.25 in J033829.31 + 002156.3 and 0.36 in PC1247+3406) and we also find that there are significant regions of low optical depth ($\tau < 0.1$). Our results are similar to the minimum optical depth of $\tau = 0.02 \pm 0.03$ at $z = 4.3$ found in the $z = 4.7$ quasar BR1202–0725 by Giallongo et al. (1994) and to the $2\,\sigma$ lower limit of 0.1 found by Williger et al. (1994) in the $z = 4.5$ quasar BR1033–0327. Both the Oke index and the low minimum opacity require a relatively high ionizing flux at these redshifts.

2. Observations

Long-slit spectroscopic observations of J033829.31 + 002156.3 were obtained with LRIS (Oke et al. 1995) on UT 10 Feb 1999 with a $1''\!.0$ wide slit and $400\ell/$mm grating blazed at 8500 Å (spectral resolution 8.1 Å), and on UT 17 Feb 1999 with a $1''\!.5$ wide slit, with both the $400\ell/$mm grating blazed at 8500 Å (spectral resolution 12.3 Å), and with the $300\ell/$mm grating blazed at 5000 Å (spectral resolution 17.3 Å). Seeing was $0''\!.7 - 0''\!.9$ FWHM on the first night, and $0''\!.7 - 1''\!.0$ on the second night; observations were made under dark, photometric conditions in each instance. A sequence of three exposures, shifted by $10''$ along the slit, was taken in each configuration with the position angle of the slit set to the parallactic angle for the middle exposure. This yielded net integrations of 3600 s (5542–9350 Å; 8.1 Å resolution; $1''\!.0$ slit), 3600 s (5799–9609 Å; 12.4 Å resolution; $1''\!.5$ slit), and 3000 s (3673–8708

Å; 17.3 Å resolution; 1″5 slit). A GG495 blocking filter was used to suppress second order blue light. The observations are summarized in Table 1. Calibration stars (HZ4 and HZ44) were observed at the parallactic angle for each slit/grating configuration and used to flux calibrate the data. The calibration stars used for the LRIS and HIRES data are Category 1 HST Standard Stars (Bohlin & Lindler 1992), which are part of an ongoing effort to develop a consistent set of fundamental flux standards for observations with the *Hubble Space Telescope* over the wavelength region from 1050–10000 Å based on the Oke (1990) measurements taken on the Double Spectrograph of the Palomar 5-m telescope for optical measurements. Although both HZ4 and HZ44 have long-wavelength flux calibration data measured by a variety of authors (e.g., Oke 1974; Stone 1977; Massey & Gronwall 1990), for self-consistency we use the Oke (1974, 1990) measurements. The estimated galactic extinction is $E_{B-V} = 0.10$ in this direction (Schlegel, Finkbeiner, & Davis 1998).

The HIRES (Vogt et al. 1994) observations were obtained using the red collimator and the D1 decker (1″1 × 14″ slit; resolution $R = 36,000$) on the nights of UT 14 and 15 Feb 1999 under conditions of variable seeing. The four 2400 s exposures were taken at P.A. = 100° (non-parallactic angle) using the atmospheric dispersion corrector to maintain the guide object for this observation within the guide camera field. The white dwarf standard star G191-B2B (Oke 1990) was used to correct the continuum fit, which was then flux-calibrated by comparing an appropriately smoothed spectrum with the lower resolution LRIS data. The combined LRIS spectra, smoothed to the lowest resolution data taken with the 300ℓ/mm grating (resolution 17.4 Å), is shown in Figure 1, and the HIRES spectrum in Figure 2. Prior to any extinction corrections, both continua are well fit by a flat f_ν spectrum in the line-free portions of the red spectrum, and this is shown by the dashed line.

The fluxed LRIS spectra are in excellent agreement with the photometric measurements of Fan et al. (1999), and with their estimated AB_{1450} continuum magnitude of 20.01 (35

μJy). A strong Mg II doublet is visible superposed on the C IV emission (Figure 1). We measure a doublet ratio $D_R = 1.25$ and a redshift $z = 2.304$ for this system. If the strong rest equivalent width ($W_{\lambda, rest}(2796) = 1.73$ Å) indicates a large galaxy along the line-of-sight (Bergeron & Boissé 1991; Steidel, Dickinson, & Persson 1994), the quasar may be amplified by lensing.

3. Discussion

The simplest measures of the opacity of the neutral hydrogen are the Oke and Korycanski (1982) indices. Following Schneider, Schmidt, & Gunn (1991a) and Schneider et al. (1991b) we measure the index

$$D_A = \left\langle 1 - \frac{f_\nu(\text{observed})}{f_\nu(\text{continuum})} \right\rangle$$

in the rest-frame wavelength range 1050 Å to 1170 Å, obtaining $D_A = 0.75$ in both the lower resolution spectra. This can be compared with the values of 0.55 to 0.74 measured by Schneider et al. (1991b) and Kennefick, Djorgovski, & de Carvalho (1995) in quasars in the range $z = 4.35 - 4.5$ and with the values of 0.74 obtained by Schneider et al. for the $z = 4.733$ quasar PC1158+4635 and 0.64 for the $z = 4.897$ quasar PC1247+3406. It is considerably smaller than the value of 0.9 predicted by Zhang et al. (1997) for models with the Haardt and Madau (1996) J_ν evolution, with $\Omega_b = 0.06$ and $H_0 = 50$ km s^{-1} Mpc^{-1}, suggesting that these models are underestimating J_ν/Ω_b^2 at high redshift.

This can also be examined by looking at the regions of minimum opacity in the much higher resolution HIRES spectrum. As can be seen from Figure 2, portions of the HIRES spectrum return close to the extrapolated continuum. 14% of the spectrum has $\tau < 0.1$ in the observed wavelength range $6800 - 7000$ Å if we extrapolate the continuum with a ν^0 power law. This fraction is not highly sensitive to the power law choice, and reduces only to 11% if we use a ν^1 extrapolation. The regions of minimum opacity around 6790 Å and

6948 Å have extremely low optical depth. The mean optical depth between 6946 Å and 6949 Å is -0.05 ± 0.05 for a ν^0 extrapolation and 0.05 ± 0.05 for a ν^1 extrapolation, where the errors are based only on the statistical noise in the region. In the subsequent discussion we will adopt what we believe is a conservative limit of $\tau < 0.1$ at this redshift of 4.72.

For a uniformly distributed IGM and $q_0 = 0.5$,

$$\tau = 1400 \, h_{50}^3 \, \Omega_b^2 \, J_{-22}^{-1} \, T_4^{-0.75} \left(\frac{1+z}{5.72} \right)^{4.5}$$

where h_{50} is the Hubble constant in units of 50 km s^{-1} Mpc^{-1}, J_{-22} is the metagalactic flux at the Lyman edge ($J_\nu = 10^{-22} J_{-22} (\nu/\nu_{912})^{-\alpha}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} with $\alpha = 0.7$) and T_4 is the temperature of the gas in units of 10^4 K (Giallongo et al. 1994). For $\tau < 0.1$ we obtain

$$\Omega_b \, h_{50}^2 < 8.4 \times 10^{-3} \, h_{50}^{0.5} \, J_{-22}^{0.5} \, T_4^{0.375}.$$

Using Haardt & Madau's value of $J_{-22} = 0.4$ at $z = 4.72$ would give $\Omega_b h_{50}^2 < 0.005 \, h_{50}^{0.5} \, T_4^{0.375}$.

If, however, the minimum opacity arises in cosmic minivoids, this number must be corrected upward to allow for the underdensity in these regions. Simulations with current cosmological parameters suggest that the profile of the density distribution at $z = 5$ will be centered on a mode of an underdensity of about 0.5, and will have very little volume indeed at underdensities of 0.2 or less (e.g., Zhang et al. 1998). The underdense regions are relatively cold, with temperatures of around 5000 K. If we conservatively assume that the minimum opacity portions of the current spectrum arise in regions which are underdense by a factor of five, and set $T_4 = 0.5$, we would obtain $\Omega_b h_{50}^2$ of 0.019 for $J_{-22} = 0.4$. We can compare this estimate of the baryon density to that derived from measurements of primordial D/H. The lowest value of $\Omega_b \, h_{50}^2$ (0.02) that might currently be possible would correspond to $D/H = 2 \times 10^{-4}$ (Songaila, Wampler, & Cowie 1997; Webb et al. 1997) whereas $D/H = 3.3 \times 10^{-5}$, or $\Omega_b \, h_{50}^2 = 0.077 \pm 0.006$, is obtained by Tytler's group (Burles & Tytler 1998). Even with the minimum $\Omega_b \, h_{50}^2 = 0.02$, we require $J_{-22} > 0.4$ at $z = 4.72$,

whereas the low D/H value would require $J_{-22} > 7$, more than an order of magnitude higher than the Haardt-Madau estimate.

REFERENCES

Bergeron, J., & Boissé, P. (1991), A&A, 243, 344

Bohlin, R., & Lindler, D. 1992, Space Telescope Science Institute Newsletter, 9, No. 2, 19

Burles, S., & Tytler, D. 1998, ApJ, 499, 699

Cen, R., Miralda-Escudé, J., Ostriker, J. P., & Rauch, M. 1994, ApJ, 437, L9

Fan, X., et al. 1999, AJ, 118, in press, astro-ph/9903237

Field, G. B. 1959, ApJ, 129, 536

Giallongo, E., D'Odorico, S., Fontana, A., McMahon, R. G., Savaglio, S., Cristiani, S., Molaro, P., & Trevese, D. 1994, ApJ, 425, L1

Gunn, J. E., & Peterson, B. A. 1965, ApJ, 142, 1633

Haardt, F., & Madau, P. 1996, ApJ, 461, 20

Kennefick, J. D., Djorgovski, S. G., & de Carvalho, R. R. 1995, ApJ, 110, 2553

Massey, P., & Gronwall, C. 1990, ApJ, 358, 344

Meiksin, A. 1994, ApJ, 431, 109

Oke, J. B. 1974, ApJS, 27, 21

———. 1990, AJ, 99, 1621

Oke, J. B., et al. 1995, PASP, 107, 375

Oke, J. B., & Korycanski, D. G. 1982, ApJ, 255, 11

Reisenegger, A., & Miralda-Escudé, J. 1995, ApJ, 449, 476

Scheuer, P. A. G. 1965, Nature, 207, 963

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525

Schneider, D. P., Schmidt, M., & Gunn, J. E. 1991a, AJ, 101, 2004

———. 1991b, AJ, 102, 837

Shklovskij, I. S. 1964, Astron. Tsirkulyar, AN SSR, 3, 303

Songaila, A., Wampler, E. J., & Cowie, L. L. 1997, Nature, 385, 137, astro-ph/9611143

Steidel, C. C., Dickinson, M., & Persson, S. E. 1994, ApJ, 437, L75

Stone, R. P. S. 1977, ApJ, 218, 767

Vogt, S. S., et al. 1994, S.P.I.E., 2198, 362

Webb, J. K. et al. 1997, Nature 388, 250

Williger, G. M., Baldino, J. A., Carswell, R. F., Cooke, A. J., Hazard, C., Irwin, M. J., McMahon, R. G., & Storrie-Lombardi, L. J. 1994, ApJ, 428, 574

Zhang, Y., Anninos, P., & Norman, M. L. 1995, ApJ, 453, L57

Zhang, Y., Anninos, P., Norman, M. L., & Meiksen, A. 1997, ApJ, 485, 496

Zhang, Y., Meiksen, A., Anninos, P., & Norman, M. L. 1998, ApJ, 495, 63

Table 1.   Spectroscopic Observations of J033829.31+002156.3

UT Date	A.M.	t_{exp} (s)	$\lambda\lambda$ Range[a] (Å)	Slit (arcsec)	PA[b] (°)	Resolution[c] (Å)	Grating[d]	FWHM[e] (arcsec)
LRIS								
10 Feb 1999	1.08	3600	5542–9350	1.0×274	28.0	8.1	400/8500	0.72
17 Feb 1999	1.12	3600	5799–9609	1.5×274	50.0	12.4	400/8500	0.71
17 Feb 1999	1.30	3000	3673–8708	1.5×274	62.0	17.3	300/5000	1.00
HIRES								
14 Feb 1999	1.15	2400	$\cdots$	1.1×14	100.0	$\cdots$	Red	3.0
15 Feb 1999	1.10	7200	$\cdots$	1.1×14	100.0	$\cdots$	Red	1.2

[a]The usable wavelength range for the multi-order HIRES data is $\sim 6800 - 8000$Å

[b]Set close to estimated parallactic angle at mid-exposure in the sequence of LRIS observations

[c]$R = 36000$ for HIRES

[d]Identified by ruled ℓ/mm and blaze wavelength in Å for LRIS; for HIRES this is the RED configuration with D1 decker

[e]Measured FWHM of quasar profile on slit

Table 2. $z = 2.304$ Mg II Absorber

ID	λ (Å)	$W_{\lambda, rest}$ (Å)
Mg II 2796	9236.7	1.73
Mg II 2803	9260.4	1.38

Fig. 1.— Both the 300ℓ/mm and 400ℓ/mm fluxed LRIS spectra are shown, in μJy *versus* wavelength. The 300ℓ/mm spectrum is shown over the wavelength range $4000 - 8200$ Å and the combined 400ℓ/mm data from 5700 Å to 9700 Å. The spectra agree extremely well in the overlap region. The dashed and dotted lines show ν^0 and ν^1 continuum fits, normalized to the region $7700 - 8000$ Å, which lies redward of the atmospheric A band but blueward of the Si IV emission line.

Fig. 2.— The flux-calibrated HIRES spectrum over the range $6800 - 7700$ Å. The spectrum has been smoothed to a resolution of 2 Å. The dotted and dashed lines show the same continuum fits as in Figure 1.
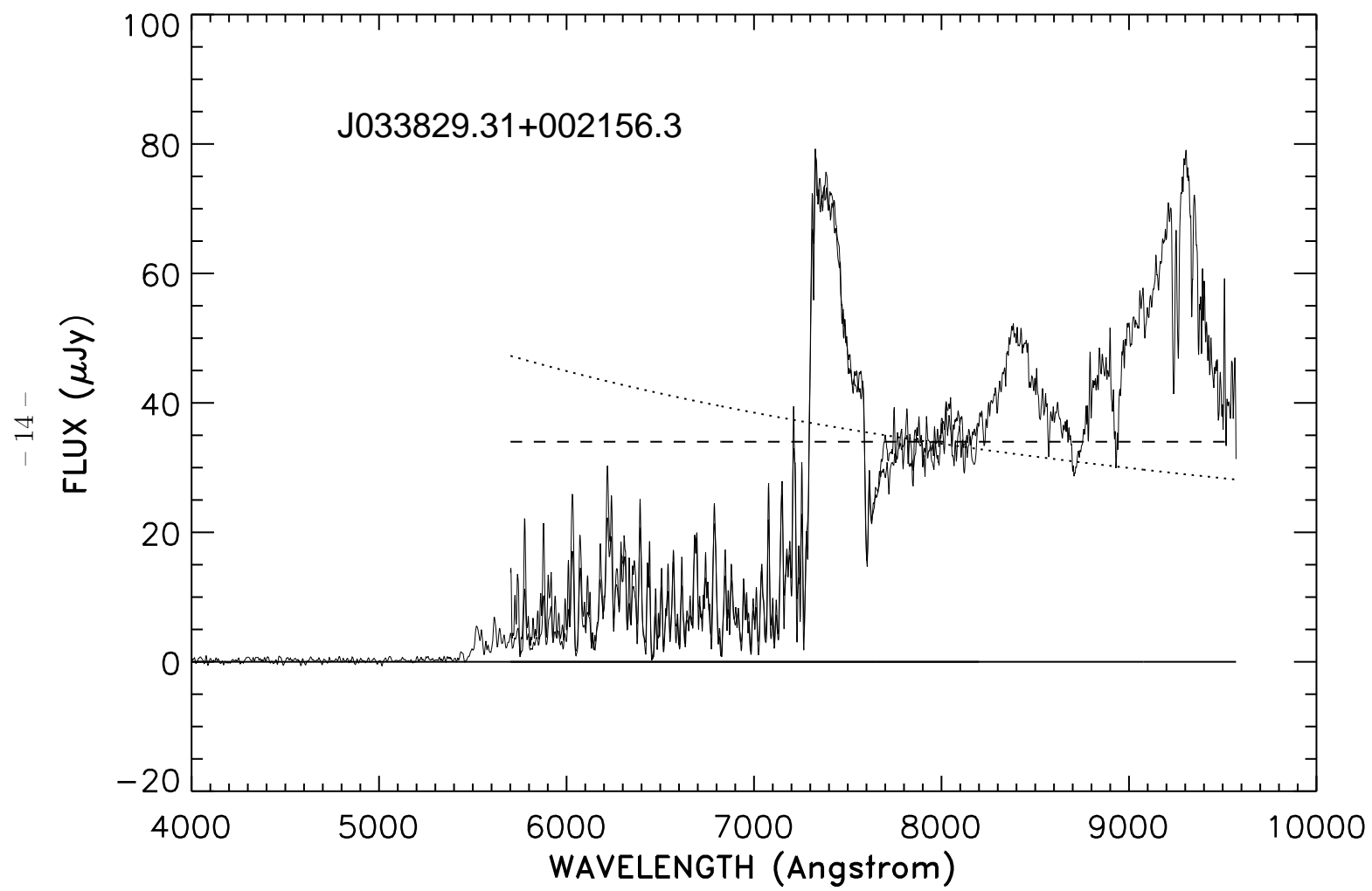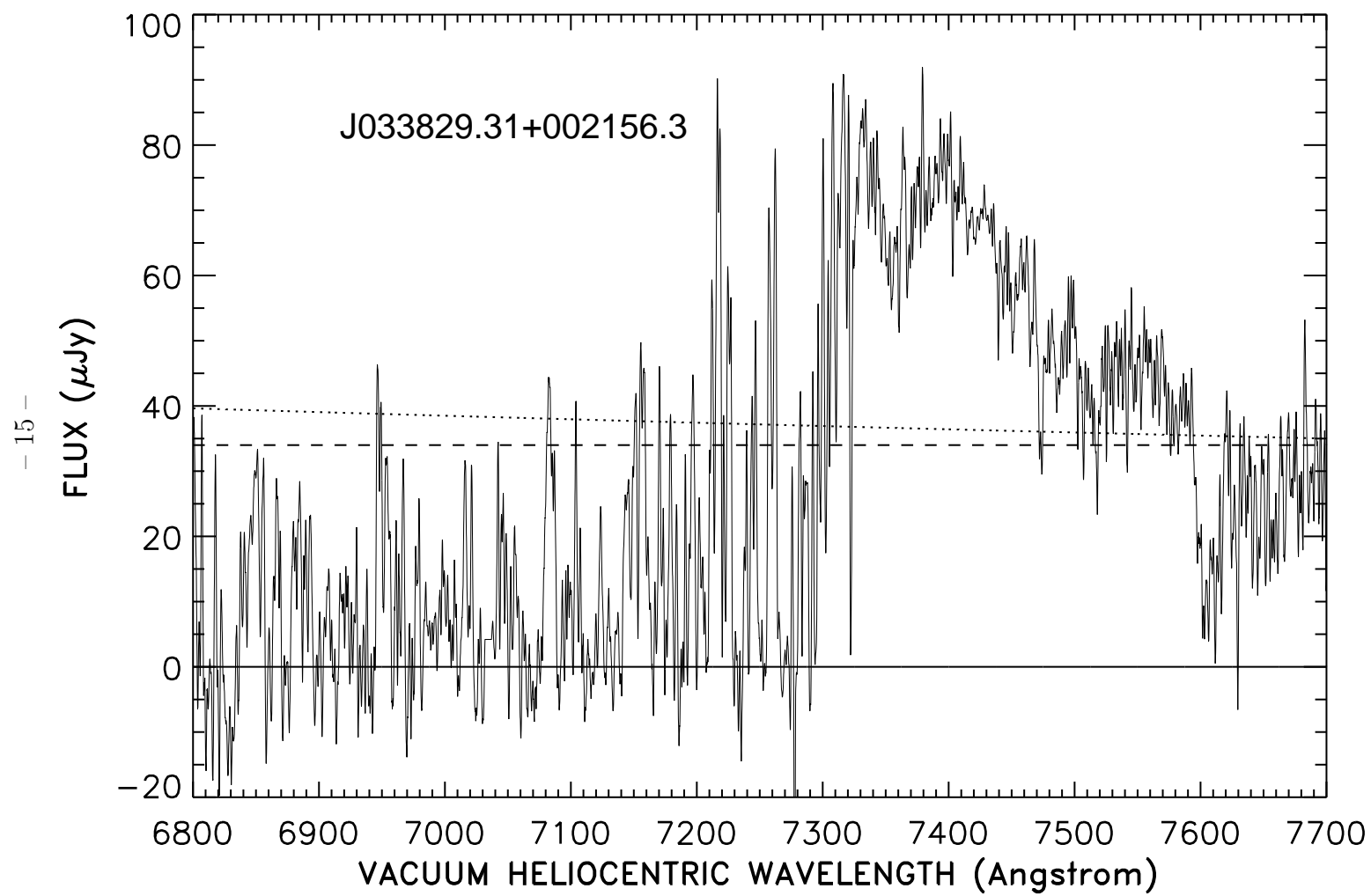
Fig. 1.—

Fig. 2.—